Hot Subdwarf Stars and Related Objects
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Hypervelocity Stars: Young and Heavy or Old and Light?

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Abstract. The first three hyper-velocity stars (HVS) unbound to the Galaxy were serendipitously discovered in 2005. The only suggested origin of hyper-velocity stars is the Galactic Centre as it hosts a super-massive black hole capable of accelerating stars to such high velocities. Only one HVS, the sdO star US 708, is known to be an old low mass star, while HE 0437−5439 is an apparently normal early-type B-star, too short-lived to originate from the Galactic Centre, but could possibly come from the LMC. A systematic survey has led to the discovery of seven new HVS of late B-type (similar to the prototype HVS1), which can either be massive stars ($\approx 3\,M_\odot$) or horizontal branch stars, sufficiently long-lived to have travelled from the Galactic Centre. We present new spectral analyses of five known HVS as well as of a newly discovered candidate. It is possible that the late B-type HVS are a mix of main sequence and evolved BHB stars. In view of the time scale problem we revisit HE 0437−5439 and discuss a possible subluminous nature of this star.

1. Introduction

Stars moving at velocities higher than the Galactic escape velocity were first predicted to exist by Hills (1988). The first such hyper-velocity stars (HVS) were discovered serendipitously only recently (Brown et al. 2005; Hirsch et al. 2005; Edelmann et al. 2005). A systematic search for such objects has resulted in the discovery of seven additional HVS up to now (Brown et al. 2006a,b, 2007).

Hills (1988) predicted that the tidal disruption of a binary by an super-massive black hole (SMBH) could lead to the ejection of stars with velocities exceeding the escape velocity of our Galaxy. The Galactic Centre (GC) is the suspected place of origin of the HVSs as it hosts an SMBH. Yu & Tremaine (2003) investigated Hill's SMBH slingshot mechanism further and estimate a HVS formation rate of $10^{-5}\,\mathrm{yr}^{-1}$ which implies $\approx 2\,000$ HVS in a sphere of 120 kpc radius (Brown et al. 2006a). If the GC hosts a tight binary of a SMBH and an intermediate black hole (IMBH), the formation rate for HVS would be ten times as large (Yu & Tremaine 2003).

Gnedin et al. (2005) and Bromley et al. (2006) showed that the space distribution of HVSs provides significant constraints on the shape and density distribution of the Galactic dark matter halo. Brown et al. (2007) estimate that 100 HVS are possibly enough to constrain ejection mechanisms and (dark matter) potential models for the Galaxy.

In view of the great importance of hyper-velocity stars to astrophysics it is worthwhile to study each of the known HVS in as much detail as possible. As the stars are found at high Galactic latitudes one might expect them to be old, low mass stars. However, there is evidence to the opposite as HVS1 and HE 0437−5439 show photometric and spectroscopic signatures of young massive stars. US 708 (HVS2) is the only bona-fide old, low mass star amongst the known HVS because it is a very hot helium-rich sdO star. All other HVS discovered are either late B-type dwarf stars (of about 3 $M_{\odot}$) or blue horizontal branch stars. Additional observational evidence is lacking up to now to distinguish between these options.

In the context of this conference we shall discuss whether some of the HVS stars (besides US 708) could be related to the (extreme) horizontal branch. We begin with a description of the hyper-velocity sdO star and present preliminary results of spectral analyses of HVS of late B type in Section 3. Section 4 presents speculations about the early B-type star HE 0437−5439 for which a LMC origin was suggested. Before concluding we present a preliminary spectral analysis of a candidate HVS, a bright B-type giant, in Section 5.

2. US 708 – A Hyper-Velocity Subdwarf O Star

Amongst sdO stars drawn from the Sloan Digital Sky Survey, Hirsch et al. (2005) discovered a hyper-velocity star, US 708, with a heliocentric radial velocity of $+708\pm15\,\mathrm{km\,s^{-1}}$. A quantitative NLTE model atmosphere analysis of optical spectra obtained with the KECK I telescope (see Fig. 1) shows that US 708 is a *helium-enriched* sdO and that its atmospheric parameters ($T_{\rm eff}$=44 500 K, $\log(g) = 5.25$) are typical for this spectral class (Ströer et al. 2007). Adopting the canonical mass of half a solar mass from evolution theory the corresponding distance is 19 kpc. Its galactic rest frame velocity is at least $757\,\mathrm{km\,s^{-1}}$, much higher than the local Galactic escape velocity (about $430\,\mathrm{km\,s^{-1}}$) indicating that the star is unbound to the Galaxy.

Numerical kinematical experiments were carried out to reconstruct the path of US 708 from the GC. US 708 needs about 36 Myr to travel from the GC to its present position, which is shorter than its evolutionary lifetime. Hence it is plausible that the star might have originated from the GC, which can be tested by measuring accurate proper motions.

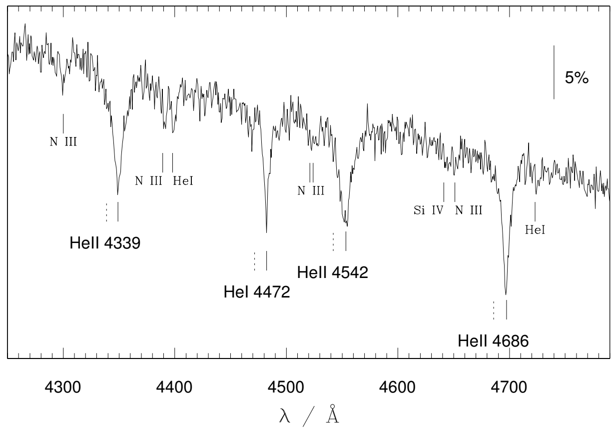

Figure 1. Section of the spectrum of US 708. Rest-wavelengths of the strongest lines are marked as dashed lines. Note the large redshifts (from Hirsch et al. 2005).

3. Hyper-Velocity Stars: Massive or Low Mass?

The hyper-velocity stars discovered in the systematic survey of Brown et al. (2006a,b, 2007) are all of late B spectral type. As the location of the main sequence intersects with that of the horizontal branch in the HRD near this spectral type, it is not clear a priori whether the stars are un-evolved massive stars of about $3\,M_\odot$ or evolved low mass stars of about half a solar mass. Hence we lack crucial information on their distances which is important for an analysis of their kinematics.

Medium resolution (1.2Å) MMT spectra of the HVS stars 1,4,5,6, and 7 were obtained by Brown and the observed Balmer lines were matched to a grid of synthetic spectra calculated from metal-line blanketed LTE model atmospheres (see Heber et al. 2000; O'Toole & Heber 2006) assuming solar helium abundance. The helium line 4026Å was included in the fit, but turned out to be too weak to reliably constrain the helium abundance in most cases. Preliminary results are shown in Fig. 2.

From their position in the ($T_{\rm eff}$, $\log g$-) diagram it is evident that they can either be distant (intrinsically bright) main sequence B (Fig. 2, upper panel) or closer (intrinsically faint) blue horizontal branch stars (BHB, Fig. 2, lower panel). Obviously, the available information ($T_{\rm eff}$, $\log g$) is insufficient to distinguish a BHB star from a main sequence B star.

Hence, we inspected the line profiles in more detail. For HVS 1 the observed profiles are broader than predicted by the synthetic spectra, which we attribute to rotation. By varying the projected rotational velocity we find $v \sin i = 190\,{\rm km\,s^{-1}}$ to fit best. There is also evidence for rotational broadening in HVS 6. Such high projected rotation velocities would favour a main sequence nature of the stars. Photometric investigations revealed HVS 1 to be a slowly pulsating B-type main sequence stars (Fuentes et al. 2006). The helium abundance of HVS 7 is subsolar (almost by a factor of one hundred) which is typical for a horizontal branch star but rather unusual for a main sequence star.

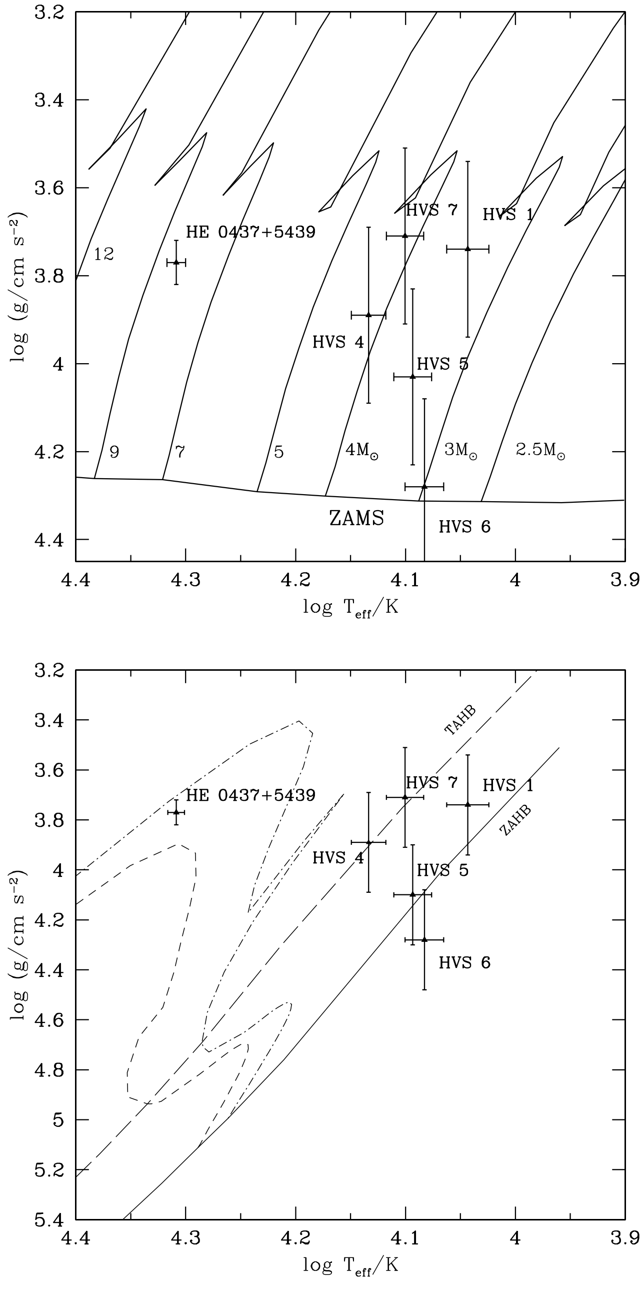

Figure 2. Position of the B-type HVSs (including HE 0437−5439) in a ($T_{\rm eff}$, $\log(g)$) diagram and comparison with evolutionary models and tracks to determine masses and evolutionary ages. The atmospheric parameters were derived assuming zero rotation velocity and solar helium abundance except for HVS 1. *Top panel*: comparison with models for massive stars from Schaller et al. (1992). *Lower panel*: comparison with models for the Horizontal Branch. The ZAHB is the zero age horizontal branch, while TAHB (dashed) is the terminal age horizontal branch. Post-EHB tracks for 0.485 $M_\odot$ (short-dashed) and 0.49 $M_\odot$ (dashed dotted) are from Dorman et al. (1993).

Thus it is possible that the late B-type HVS are a mix of main sequence and evolved BHB stars.

4. HE 0437−5439 Revisited

The late B type stars as well as the sdO star are sufficiently long-lived ($\approx$ 100 Myr) to have reached their present location in the Galactic halo after ejection from the GC. The third HVS, HE 0437−5439 (Edelmann et al. 2005) is much shorter-lived as it is of early B-type. $T_{\rm eff} = 20\,3502s$K K, $\log g = 3.77$, and a solar helium abundance were derived by a quantitative analysis of high-resolution spectra. Solar abundances are consistent with the observations to within a factor of two to three. Both, the chemical composition and the moderate rotational velocity ($v \sin(i) = 54\,{\rm km\,s^{-1}}$) of HE 0437−5439 were considered evidence for a main sequence nature. Accordingly, the star lies at similar distance (60 kpc) as the other HVSs, but is of much higher mass ($8\,{\rm M_\odot}$).

Numerical kinematical experiments were carried out to trace the trajectory of HE 0437−5439 from the Galactic Centre to its present location in the Galactic halo. However, its travel time (100 Myr) was found to be much longer than its main sequence lifetime ($\approx$ 25 Myr) rendering a GC origin unlikely. Edelmann et al. (2005) suggested that the star could have originated from the Large Magellanic Cloud (LMC) as it is much closer to it (18 kpc) than to the GC. Indeed HE 0437−5439 can reach its position from the centre of the LMC in less than its life time if its ejection velocity were of the order of $500\,{\rm km\,s^{-1}}$ or larger. However, no SMBH is known to exist in the LMC.

As the focus of this conference lies with hot subluminous stars we feel free to discuss a somewhat speculative solution to the time scale problem. Let us assume that HE 0437−5439 is not a young massive star at all, but merely mimics it very closely. Comparing the position of HE 0437−5439 in the ($T_{\rm eff}$, $\log g$) diagram to evolutionary tracks (Fig. 2) we conclude that HE 0437−5439 could be a post-HB star of $\approx 0.5\,{\rm M_\odot}$. Usually, blue horizontal branch stars in the halo of our Galaxy show peculiar abundance pattern and very low projected rotation velocity ($\leq 10\,{\rm km\,s^{-1}}$) quite different from those of early type MS stars. So, how could a BHB star maintain (i) a high rotational velocity as well as (ii) normal abundances? (i) If the SMBH slingshot mechanism is valid, the star was in a binary before ejection. In that system the rotation would have been tidally locked to the orbit, enforcing a high rotation rate if the binary system was sufficiently close. (ii) The abundance peculiarities in BHB stars are due to atmospheric diffusion processes. To maintain normal abundances diffusion needs to be suppressed. We conjecture that rotational induced motions in the atmospheres could wash out the slow diffusive motions. The rapid rotation enforced by tidally locking could then inhibit abundances peculiarities to built up. Hence tidally locked rotation and suppression of diffusion could result in a spectrum of a BHB star that mimics that of a massive star quite closely.

If we assume a mass of $0.5\,{\rm M_\odot}$ the star would be much much closer ($d =$ 14 kpc). Ejected at $927\,{\rm km\,s^{-1}}$ the proper motion required would be sufficiently large ($\mu_\alpha \cos\delta = 3.085\,{\rm mas/yr}$ and $\mu_\delta = -3.365\,{\rm mas/yr}$) to be measurable with present day instrumentation. The travel time from the GC (26 Myr) is much shorter than for a main sequence star. However the evolutionary life time for the post-HB phase is also much shorter ($\approx 10^7$ yrs). Hence the star has to have evolved from a more compact ($R = 0.2R_\odot$) extreme horizontal branch star, i.e. an sdB star (see Fig. 2, lower panel) after ejection from the GC. This poses an angular momentum problem, if angular momentum is conserved during evolution from the HB. The rotation velocity of the sdB progenitor of HE 0437−5439 would then be larger than $300\,\mathrm{km\,s^{-1}}$. This implies that the orbital period of the binary before disruption had to be 45 m or less. If HE 0437−5439 was ejected by the disruption of an sdB binary due to tidal interaction with the SMBH in the GC, the original companion would have to be very compact, possibly a neutron stars or black hole.

All in all this scenario for the origin of HE 0437−5439 appears to be far-fetched and the origin of the star as a massive one ejected from the LMC is more plausible. An accurate proper motion measurement would allow us to distinguish between the LMC origin as a massive star or the GC origin as a low mass star.

5. HD 271791 – a B-type Giant at High Velocity

In the course of our investigations of B-type stars at high Galactic latitudes we took high resolution spectra of the bright star HD 271791 ($V = 12.3$) with the ESO 2.2m telescope and the FEROS spectrograph yielding a heliocentric radial velocity of $441\,\mathrm{km\,s^{-1}}$. We determine the atmospheric parameters of HD 271791 to be $T_{\rm eff} = 17810 \pm 180\,\mathrm{K}$, $\log(g) = 3.04 \pm 0.03\,\mathrm{(cgs)}$, and $\log(n_{\rm He}/n_{\rm H}) = -0.81 \pm 0.02$. The atmospheric parameters places HD 271791 within the domain of B-type giants. The projected rotational velocity is determined by a χ^2 fit to all Balmer and helium lines. The best matching fit results in a $v\sin(i) = 124\,\mathrm{km\,s^{-1}}$ (see Fig. 3). Metal absorption lines of C II, N II, O I, O II, Ne I, Mg II, Al III, Si II, Si III, S II, and S III are clearly present in the FEROS spectrum. However, all lines are broadened due to the high rotation. This renders a quantitative abundance analysis difficult. Nevertheless, we compared synthetic spectra calculated from LTE model atmospheres (Heber et al. 2000) with different metal contents to the FEROS spectrum (see Fig. 4) and find that solar composition provides a good match to the observations.

The almost solar metal content and its high rotation suggests that HD 271791 is a young massive star. Comparing its position in the ($T_{\rm eff}$, $\log g$) diagram to evolutionary tracks (Schaller et al. 1992), a mass of $11.5 \pm 0.5\,\mathrm{M_\odot}$ and a very short evolutionary time $T_{\rm evol} \approx 17\,\mathrm{Myr}$ result. Using the mass, effective temperature, gravity, and apparent magnitude we derive a distance of $d = 24\,\mathrm{kpc}$.

Unlike for the other HVS stars, proper motion measurements are available for HD 271791 and have been published in five astrometric catalogues. These values diverge quite significantly, however, most showing a very small proper motion in right ascension and a substantial one in declination. Using the measurements that roughly agree with each other, we derived a "best" value of $\mu_\alpha = -1\,\mathrm{mas/yr}$ and $\mu_\delta = 7\,\mathrm{mas/yr}$. Because of the large distance the corresponding transversal velocities are high resulting in galactic rest-frame velocities between $413\,\mathrm{km\,s^{-1}}$ and $1080\,\mathrm{km\,s^{-1}}$ for different choices of the proper motion.

Numerical kinematical experiments were performed to trace the motion of the star during its life time. None of the trajectories took the star anywhere

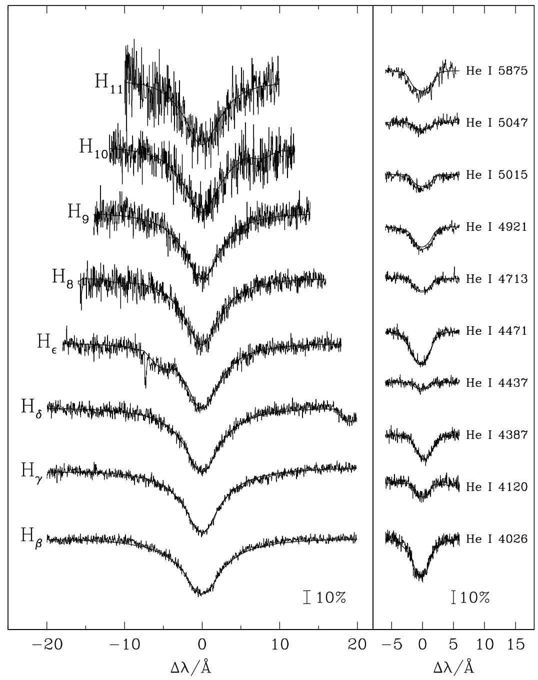

Figure 3. LTE line profile fit of the FEROS spectrum of HD 271791

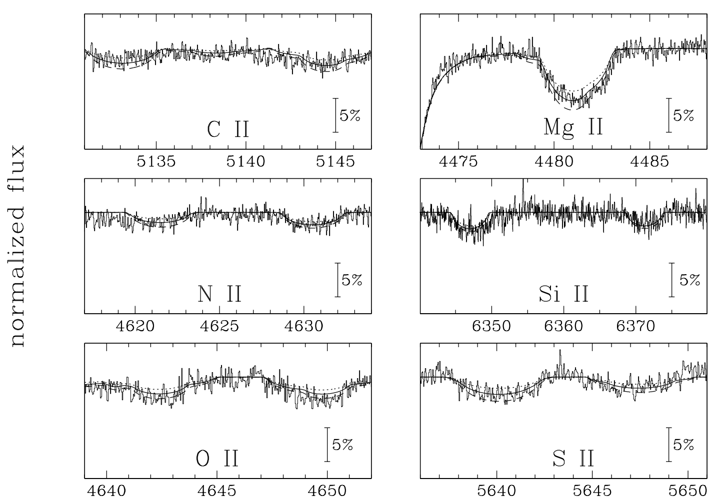

Figure 4. Selected metal line profiles in the FEROS spectrum of HD 271791 compared to synthetic spectra with solar metal abundance (solid lines), 0.5 times solar metal abundance (dotted lines), and twice solar metal abundance (dashed lines)

near the Galactic Centre. The peri-galactic distances vary mostly between 15 and 20 kpc. Therefore, it unlikely that this objects was born near the Galactic Centre. Hence, we encounter the same time scale problem as for HE 0437−5439. Again we might start to speculate about a low mass nature of HD 271791. Due to its low gravity the star would probably be in the post-AGB phase of evolution. The post-AGB phase is very short-lived and thus unlikely to be observed. Hence we regard the low mass option for HD 271791 very unlikely.

6. Conclusions

Only one HVS, the sdO star US 708 is an old low mass star, while two stars are apparently normal early-type B-stars, too short-lived to have travelled from the GC to their present positions in the Galactic halo. Seven newly discovered HVS are of late B-type (similar to the prototype HVS1), which can either be massive stars ($\approx 3\,rmM_\odot$) or horizontal branch stars, sufficiently long-lived to have travelled from the Galactic Centre. We presented new spectral analyses of five known HVS as well as of the newly discovered candidate HD 271791, an apparently normal B giant. We find evidence for rapid rotation in HVS1 and 6, and HD 271791, suggesting that they are massive stars. It may be possible that the late B-type HVS are a mix of main sequence and evolved BHB stars.

In view of the time scale problem we revisited HE 0437−5439 and discussed whether it could possibly be a subluminous star, which we, however, find unlikely because of angular momentum constraints. Accurate proper motion measurements of HE 0437−5439 are required to distinguish between a LMC origin as a massive star or a Galactic origin as a low mass star. A NLTE analysis of high-resolution spectra is underway to determine accurate abundances (Przybilla et al., in prep.). Alternative ejection scenarios need to be looked at that do not require an SMBH (Gvaramadze et al. 2007) or a much less massive IMBH ($> 1000\,\mathrm{M}_\odot$, Gualandris & Portegies Zwart 2007).

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